

# Flavor dependence of jet quenching in $pp$ collisions and its effect on the $R_{AA}$ for heavy mesons

B.G. Zakharov<sup>1</sup>

<sup>1</sup>*L.D. Landau Institute for Theoretical Physics, GSP-1, 117940, Kosygina Str. 2, 117334 Moscow, Russia*  
(Dated: September 24, 2015)

We study the flavor dependence of the medium modification factor  $R_{pp}$  for  $pp$  collisions for scenario with formation of a small-size quark-gluon plasma (QGP) for RHIC ( $\sqrt{s} = 0.2$  TeV) and LHC ( $\sqrt{s} = 2.76$  TeV) energies. We find that at  $p_T \sim 10$  GeV the pion spectrum is suppressed by  $\sim 20 - 30$  (25 - 35)% for RHIC (LHC), for  $D$  ( $B$ ) mesons the suppression effect is smaller by a factor of  $\sim 0.7 - 0.8$  (0.5). The flavor hierarchy  $R_{pp}^\pi < R_{pp}^D < R_{pp}^B$  is held at  $p_T \lesssim 20$  GeV for RHIC and at  $p_T \lesssim 70$  GeV for LHC. This gives a sizeable reduction of the heavy-to-light ratios of the nuclear modification factors  $R_{AA}$  as compared to that in the standard scenario without the QGP production in  $pp$  collisions.

PACS numbers:

## I. INTRODUCTION

There is general consensus that the observed in experiments on  $AA$  collisions at RHIC and LHC suppression of the high- $p_T$  particle spectra (jet quenching) is due to radiative and collisional parton energy loss in the QGP formed in the initial stage of  $AA$  collisions. In the scenario with formation of a mini fireball of the QGP in  $pp$  collisions a similar mechanism should suppress particle spectra as compared to the predictions of the standard pQCD that neglect the final state interaction (FSI) effects for fast partons produced in hard reactions. In this case the measured  $pp$  inclusive cross section will differ from that predicted by the pQCD,  $d\sigma_{pert}(pp \rightarrow hX)/d\mathbf{p}_T dy$ , by the medium modification factor  $R_{pp}$

$$R_{pp} = \frac{d\sigma(pp \rightarrow hX)/d\mathbf{p}_T dy}{d\sigma_{pert}(pp \rightarrow hX)/d\mathbf{p}_T dy}, \quad (1)$$

where the numerator is the real  $pp$  inclusive cross section accounting for the FSI effects in the mini-QGP. Of course the  $R_{pp}$  is not directly measurable quantity, because the spectrum with the FSI effects switched off is unknown. Nevertheless, it is clearly of great interest for understanding the uncertainties of the standard pQCD predictions due to the FSI higher twist effects. Also, the medium suppression in  $pp$  collisions is important for theoretical predictions for the nuclear modification factor  $R_{AA}$  for  $AA$  collisions, because the  $pp$  baseline spectrum, that is necessary for evaluating the  $R_{AA}$ , should account for the medium effects in the mini-QGP. In principle, the medium modification of jets in  $pp$  collisions can be studied experimentally by measuring the multiplicity dependence of the direct photon-triggered fragmentation functions (FFs) [1].

The idea that the QGP may be produced in  $pp$  collisions has attracted much attention in recent years (see, for instance, [2–7]). It is mostly due to observation of the ridge effect in high multiplicity  $pp$  events at  $\sqrt{s} = 7$  TeV by the CMS collaboration [8], which may be caused by

the transverse flow of the produced mini-QGP fireball. It is important that the conditions for the mini-QGP formation in  $pp$  collisions are better in jet events, because the multiplicity of soft off-jet particles (the so-called underlying events (UE)) is enhanced by a factor of  $\sim 2.5$  [9] as compared to minimum bias events. Therefore, even at RHIC energies  $\sqrt{s} \sim 0.2$  TeV the UE multiplicity may be high enough for the QGP formation. The scenario with mini-QGP in jet  $pp$  events is supported by the preliminary data for  $pp$  collisions at  $\sqrt{s} = 7$  TeV from ALICE [10] indicating that the jet FFs become softer with increase of the UE multiplicity.

In [1, 11] we have addressed jet quenching in  $pp$  collisions for light hadrons within the model of jet quenching of [12] (see also [13–15]) based on the light-cone path integral (LCPI) approach [16] to induced gluon emission. We studied the medium modification of the  $\gamma$ -triggered and inclusive FFs in  $pp$  collisions [1] and evaluated  $R_{pp}$  for charged hadrons [11]. It was found that the medium effects in the mini-QGP in  $pp$  collisions may be quite strong, say, at  $p_T \sim 10$  GeV the spectra are suppressed by  $\sim 20 - 30\%$  at RHIC energy  $\sqrt{s} = 0.2$  TeV and by  $\sim 25 - 35\%$  at LHC energy  $\sqrt{s} = 2.76$  TeV.

In the present letter we study flavor dependence of the  $R_{pp}$ . It is of great interest for understanding the accuracy of the pQCD predictions for heavy quark production in  $pp$  collisions. Also, the flavor dependence of  $R_{pp}$  is important for theoretical predictions of  $R_{AA}$  for heavy flavors. The question of jet quenching for heavy flavors has attracted much attention in recent years (see [17] for a short review) due to the observation of strong suppression of single (non-photonic) electrons from decays of the heavy mesons in experiments at RHIC [18, 19] (the “heavy quark puzzle”). The recent measurements at LHC of  $R_{AA}$  for electrons [20] and for  $D$  mesons [21] also show a strong suppression effect. It seems to be difficult to reconcile with the expected dead cone suppression of the radiative energy loss for heavy quarks predicted in [22]. A subsequent reanalysis [23] of the quark mass dependence of induced gluon radiation within the LCPI approach [16] demonstrated that due to the quan-

tum finite-size effects, ignored in the dead cone model [22], the quark mass suppression of radiative energy loss at low energies ( $\lesssim 20 - 30$  GeV) turns out to be significantly weaker than predicted in [22]. And at energies  $\gtrsim 100$  GeV the radiative energy loss even rises with the quark mass. Calculations of  $R_{AA}$  for electrons and  $D$  mesons in the scenario without the QGP formation in  $pp$  collisions performed in [14, 15] using the LCPI approach [16] have shown reasonable agreement with experimental data. However, the experimental error bars for  $R_{AA}$  for heavy flavors are very large. Also, the experimental data (especially for the non-photonic electrons from RHIC [18, 19]) are restricted to relatively low  $p_T$ , where the assumption of dominance of the radiative energy loss and the relativistic approximation  $m_Q/E_Q \ll 1$  for heavy quarks (especially for  $b$ -quark) used in [14, 15] may be invalid. Therefore, it is probably too early to conclude that the “heavy quark puzzle” is solved, and the flavor dependence of the nuclear modification factors deserves further investigation. In the present work we study possible effect of the mini-QGP formation in  $pp$  collisions on the heavy-to-light ratios of the nuclear modification factors in  $AA$  collisions, which is connected to reduction of the medium suppression for heavy quarks in  $pp$  collisions.

## II. SKETCH OF THE THEORETICAL FRAMEWORK

We simulate jet quenching in  $pp$  collisions within the approach of [11]. It is qualitatively similar to the scheme developed for  $AA$  collisions in [12], which has been successfully used in our several previous analyses of jet quenching in  $AA$  collisions [13–15]. So only a brief outline of important points of our theoretical framework will be given here. The interested reader is directed to [11, 12] for details.

For the perturbative inclusive  $pp$ -cross section we use the standard formula

$$\frac{d\sigma_{\text{pert}}(pp \rightarrow hX)}{d\mathbf{p}_T dy} = \sum_i \int_0^1 \frac{dz}{z^2} \times D_{h/i}(z, Q) \frac{d\sigma(pp \rightarrow iX)}{d\mathbf{p}_T^i dy}, \quad (2)$$

where  $\mathbf{p}_T$  is the particle transverse momentum,  $y$  is rapidity (we will consider the central region  $y = 0$ ),  $D_{h/i}$  is the vacuum parton  $\rightarrow$  particle FF, and  $d\sigma(pp \rightarrow iX)/d\mathbf{p}_T^i dy$  is the ordinary LO pQCD hard cross section,  $\mathbf{p}_T^i = \mathbf{p}_T/z$  is the initial parton transverse momentum. For the initial virtuality we take  $Q = p_T^i$ . In calculating  $R_{pp}$  we write the real medium modified  $pp$  cross section, that enters the numerator of (1), in a form similar to (2)

$$\frac{d\sigma_m(pp \rightarrow hX)}{d\mathbf{p}_T dy} = \sum_i \int_0^1 \frac{dz}{z^2} \times D_{h/i}^m(z, Q) \frac{d\sigma(pp \rightarrow iX)}{d\mathbf{p}_T^i dy}, \quad (3)$$

where  $D_{h/i}^m$  is now the medium-modified FF for  $i \rightarrow h$  transition in the presence of the mini-QGP fireball. It is implicit that  $D_{h/i}^m$  is averaged over the jet production point, and the impact parameter of  $pp$  collision. As in [11], we used the distribution of hard processes in the impact parameter plane obtained using for the parton distribution in the transverse plane the transverse density distribution for quarks in the MIT bag model.

In the standard scenario without the QGP formation the nuclear modification factor for  $AA$  collisions (we denote it  $R_{AA}^{st}$ ) in the scheme of [12] for a given impact parameter  $b$  reads

$$R_{AA}^{st}(b, \mathbf{p}_T, y) = \frac{dN(AA \rightarrow hX)/d\mathbf{p}_T dy}{T_{AA}(b) d\sigma_{\text{pert}}(NN \rightarrow hX)/d\mathbf{p}_T dy}, \quad (4)$$

where  $T_{AA}(b) = \int d\boldsymbol{\rho} T_A(\boldsymbol{\rho}) T_A(\boldsymbol{\rho} - \mathbf{b})$ ,  $T_A$  is the nucleus profile function, and the numerator of (4) (we omit the argument  $b$ ) is given by

$$\frac{dN(AA \rightarrow hX)}{d\mathbf{p}_T dy} = \int d\boldsymbol{\rho} T_A(\boldsymbol{\rho}) T_A(\boldsymbol{\rho} - \mathbf{b}) \times \frac{d\sigma_m(NN \rightarrow hX)}{d\mathbf{p}_T dy}. \quad (5)$$

Here  $d\sigma_m(NN \rightarrow hX)/d\mathbf{p}_T dy$  is the medium-modified  $NN \rightarrow hX$  cross section, which is given by the formula (3) for  $NN$  collisions with the medium-modified FF for the QGP produced in  $AA$  collision. In the scenario with the mini-QGP formation in  $NN$  collisions the theoretical  $R_{AA}$  (which should be compared with the experimental  $R_{AA}$ ) can be written as

$$R_{AA} = R_{AA}^{st}/R_{pp}. \quad (6)$$

Because experimentally  $R_{AA}$  is defined as the ratio of the measured  $AA \rightarrow hX$  cross section to the binary scaled experimental  $NN \rightarrow hX$  cross section, and the latter includes the FSI effects in the mini-QGP produced in  $NN$  collisions (hereafter we ignore the difference between the FSI effects in  $pp$ ,  $pn$  and  $nn$  collisions).

As in [12], we evaluate  $D_{h/i}^m$  for each fast parton trajectory as

$$D_{h/i}^m(Q) = D_{h/j}(Q_0) \otimes D_{j/k}^{in} \otimes D_{k/i}(Q), \quad (7)$$

where  $\otimes$  denotes  $z$ -convolution,  $D_{k/i}$  is the parton DGLAP  $i \rightarrow k$  FF,  $D_{j/k}^{in}$  is the parton  $j \rightarrow k$  FF in the QGP accounting for parton energy loss, and  $D_{h/j}$  is FF for the parton  $j \rightarrow h$  transition outside the QGP. For the stage outside the QGP for light partons we use for the  $D_{h/j}(Q_0)$  the KKP [24] FFs with  $Q_0 = 2$  GeV.

And for the FFs  $c \rightarrow D$  and  $b \rightarrow B$  we use the Peterson parametrization

$$D_{H/Q}(z) \propto \frac{1}{z[1 - (1/z) - \epsilon_Q/(1 - z)]^2} \quad (8)$$

with  $\epsilon_c = 0.06$  and  $\epsilon_b = 0.006$ . The DGLAP FFs have been obtained with the help of the PYTHIA event generator [25]. The medium-modified FFs were computed using the induced gluon spectrum in the form obtained in [26]. We account for the (relatively small [27]) collisional energy loss by redefining the initial QGP temperature in our formulas for the medium-modified FFs related to induced gluon emission (see [12] for details).

For the quasiparticle masses of light quarks and gluon in the QGP we use the values  $m_q = 300$  and  $m_g = 400$  MeV supported by the analysis of the lattice data [28], for  $c$  and  $b$  quark masses we take  $m_c = 1.2$  GeV and  $m_b = 4.75$  GeV. We use the Debye mass  $\mu_D$  in the QGP obtained in the lattice analysis [29], which gives  $\mu_D/T$  slowly decreasing with  $T$  ( $\mu_D/T \approx 3$  at  $T \sim 1.5T_c$ ,  $\mu_D/T \approx 2.4$  at  $T \sim 4T_c$ ).

We use (both for radiative and collisional energy loss) running  $\alpha_s$  frozen at low momenta at some value  $\alpha_s^{fr}$ . For gluon emission in vacuum for this parametrization a reasonable choice is  $\alpha_s^{fr} \approx 0.7 - 0.8$  [30, 31]. Since thermal effects can suppress the in-medium QCD coupling, we treat  $\alpha_s^{fr}$  as a free parameter (which may differ for  $pp$  and  $AA$  collisions). It is the only parameter that controls the strength of the medium effects in our calculations.

As in [12], we use for the QGP evolution 1+1D Bjorken's model (both for  $pp$  and  $AA$  collisions), which for the ideal gas model gives  $T_0^3 \tau_0 = T^3 \tau$ , where  $\tau_0$  is the thermalization time. We take  $\tau_0 = 0.5$  fm. For  $\tau < \tau_0$  we take medium density  $\propto \tau$ . For simplicity we neglect variation of  $T_0$  with the transverse coordinates.

We fix the initial temperature of the plasma fireball in  $pp$  collisions from the initial entropy density determined via the experimental UE multiplicity density

$$s_0 = \frac{C}{\tau_0 \pi R_f^2} \frac{dN_{ch}}{d\eta}. \quad (9)$$

Here  $C = dS/dy / dN_{ch}/d\eta \approx 7.67$  [32] is the entropy/multiplicity ratio, and  $R_f$  is the typical radius of the created fireball. We use for  $R_f$  the parametrization of [33] obtained from results of simulations of  $pp$  collisions performed in [6] within the IP-Glasma model. This procedure gives [33]  $R_f[\sqrt{s} = 0.2, 2.76 \text{ TeV}] \approx [1.3, 1.44] \text{ fm}$  and  $T_0[\sqrt{s} = 0.2, 2.76 \text{ TeV}] \approx [199, 217] \text{ MeV}$ . (we use the ideal gas model of the QGP with  $N_f = 2.5$ ). Note that the initial temperatures would be higher by  $\sim 10 - 15\%$  if we used the entropy from the lattice calculations [34]. We ignore this fact, because in our analysis the temperature is an auxiliary quantity characterizing the QGP entropy. The entropy is this quantity that is only important from the point of view of parton energy loss (if we assume that the number density of the color

constituents in the QGP is approximately proportional to its entropy density). And we determine it directly from the experimental UE multiplicity density. For  $AA$  collisions  $T_0$  was fixed using the data on the charged hadron multiplicity pseudorapidity density  $dN_{ch}/d\eta$  from RHIC [35] and LHC [36]. It gives  $T_0 \approx 320$  MeV for central Au+Au collisions at  $\sqrt{s} = 200$  GeV, and  $T_0 \approx 420$  MeV for central Pb+Pb collisions at  $\sqrt{s} = 2.76$  TeV.

Note that our results for  $R_{pp}$  are not very sensitive to the size of the fireball, which is not well determined. An analysis of the stability of  $R_{pp}$  to variation of  $R_f$  performed in [11] has shown that  $\pm 30\%$  change in  $R_f$  gives a small effect on  $R_{pp}$ . This is due to a compensation between the rise of the energy loss with the fireball size (for a fixed density) and its suppression with decrease of the fireball density. In [11] we argued that the stability of  $R_{pp}$  to variation of  $R_f$  allows to expect that the transverse expansion of the medium and the variation of the initial medium density in the transverse coordinates should not have a significant impact on our results for  $R_{pp}$ .

### III. NUMERICAL RESULTS

In Fig. 1 we present the results of our calculations of  $R_{pp}$  for pions,  $D$  and  $B$  mesons for RHIC energy  $\sqrt{s} = 0.2$  TeV and LHC energy  $\sqrt{s} = 2.76$  TeV obtained for  $\alpha_s^{fr} = 0.5, 0.6$  and  $0.7$ . For pions and  $D$  mesons we show the results for  $p_T > 5$  GeV, and for  $B$  mesons for the lower limit we take  $p_T = 7$  GeV to avoid possible problems with applicability of the relativistic approximation and with treating the collisional energy loss as a small perturbation to the radiative energy loss for  $b$  quark [12]. One can see that the suppression effect due to the mini-QGP formation turns out to be quite large. At  $p_T \sim 10$  GeV the pion spectrum is suppressed by  $\sim 20 - 30$  (25 - 35)% for RHIC (LHC), for  $D$  mesons the suppression is smaller by a factor  $0.7 - 0.8$ , and for  $B$  mesons the effect is smaller by a factor of  $\sim 0.5$ . At RHIC energy all the  $R_{pp}$  flatten at  $p_T \gtrsim 15 - 20$  GeV. This occurs due to compensation between the effects from the reduction with parton energy of the relative parton energy loss  $\Delta E/E$  (which increases  $R_{pp}$ ) and from the increase of the effective power  $n_{eff}$  in the power law dependence of the hard cross section  $d\sigma/dp_T \propto p_T^{-n_{eff}}$  (which reduces  $R_{pp}$ ) with increase of parton energy. Fig. 1 shows that the medium suppression in  $pp$  collisions is not very sensitive to  $\alpha_s^{fr}$ . It is a consequence of relatively large transverse momenta  $k_T$  (relative to the initial fast parton momentum) of the emitted gluons for the small-size QGP, because they approximately scale with the QGP size,  $L_{QGP}$ , as  $1/L_{QGP}$  [11]. In [11] in calculating the nuclear modification factor  $R_{AA}$  for the scenario with mini-QGP in  $pp$  collisions we used the value  $\alpha_s^{fr} = 0.6$  in calculation of the factor  $R_{pp}$ . In the present analysis we also use this value.

Even though the medium suppression of the spectra

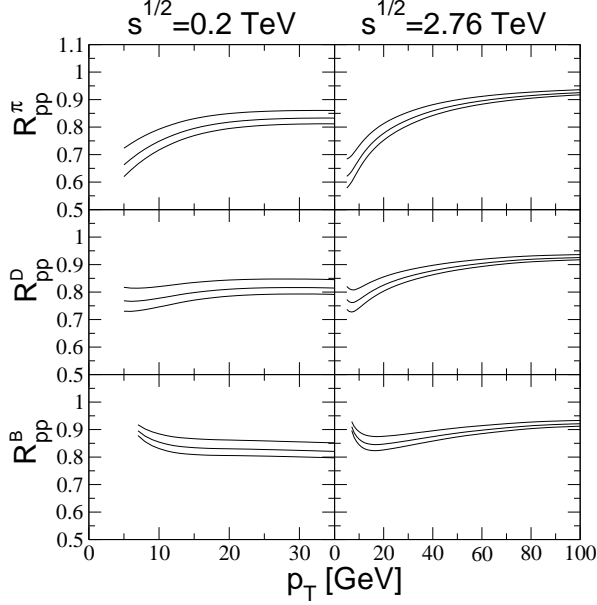


FIG. 1:  $R_{pp}$  of pions,  $D$  and  $B$  mesons at  $\sqrt{s} = 0.2$  TeV (left panels) and  $\sqrt{s} = 2.76$  TeV (right panels). From top to bottom, the curves corresponds to  $\alpha_s^{fr} = 0.5, 0.6$  and  $0.7$ .

from the QGP formation in  $pp$  collisions may be sizeable, it is hardly possible to observe it directly by comparing the experimental spectra with the theoretical predictions, because the uncertainties of the standard pQCD predictions (see for example[37–39]) are larger than the expected medium effect. For this reason it is difficult to disentangle the medium suppression and other effects that can change the pQCD predictions (such as modification of the PDFs and FFs, change of the renormalization and factorization scales) However, as was mentioned in Introduction, the preliminary ALICE data [10] on the UE multiplicity dependence of the jet FFs for  $pp$  collisions at  $\sqrt{s} = 7$  TeV support the jet quenching in  $pp$  collisions.

From Fig. 1 one sees that the flavor hierarchy  $R_{pp}^\pi < R_{pp}^D < R_{pp}^B$  is held for  $p_T \lesssim 20$  GeV for RHIC and for  $p_T \lesssim 70$  GeV for LHC. One can expect that in these  $p_T$ -regions the presence of the  $R_{pp}$  in the formula (6) for the nuclear modification factors in  $AA$  collisions will reduce the ratio of the nuclear modification factors  $R_{AA}$  for heavy and light hadrons. However, to reach a definite conclusion about the effect of  $R_{pp}$  on the heavy-to-light ratios of the nuclear modification factors  $R_{AA}$  for  $AA$  collisions one should account for the fact that in the scenario with mini-QGP formation in  $pp$  collisions the value of  $\alpha_s^{fr}$  should be somewhat increased to keep stable  $R_{AA}$  for pions (since it is assumed to be adjusted to the experimental  $R_{AA}$  of pions).

Comparison with the data on  $R_{AA}$  for light hadrons carried out in [11] has shown that for the standard scenario the RHIC data on  $R_{AA}$  for pions in Au+Au collisions for 0 – 5% centrality bin at  $\sqrt{s} = 0.2$  TeV support  $\alpha_s^{fr} \approx 0.5$ , and the LHC data on  $R_{AA}$  for charged

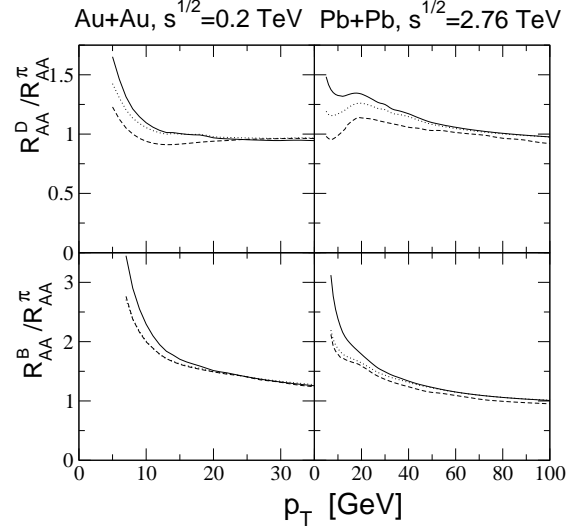


FIG. 2: The ratios  $R_{AA}^D/R_{AA}^\pi$  (upper panels) and  $R_{AA}^B/R_{AA}^\pi$  (lower panels) for 0–5% central Au+Au collisions at  $\sqrt{s} = 0.2$  TeV (left) and for 0 – 5% central Pb+Pb collisions at  $\sqrt{s} = 2.76$  TeV (right). The solid curves are for  $R_{AA}$  for  $\alpha_s^{fr} = 0.5$  (left) and  $\alpha_s^{fr} = 0.4$  (right) without  $R_{pp}$  factors in (6). The dashed curves are for  $R_{AA}$  for  $\alpha_s^{fr} = 0.6$  (left) and  $\alpha_s^{fr} = 0.5$  (right) with  $R_{pp}$  factors in (6). The dotted curves are for  $R_{AA}$  for  $\alpha_s^{fr} = 0.5$  (left) and  $\alpha_s^{fr} = 0.4$  (right) with  $R_{pp}$  factors in (6). For the dashed and dotted curves the factors  $R_{pp}$  for light and heavy flavors are calculated with  $\alpha_s^{fr} = 0.6$ .

hadrons in Pb+Pb collisions for 0 – 5% centrality bin at  $\sqrt{s} = 2.76$  TeV support  $\alpha_s^{fr} \approx 0.4$ . And for the scenario with mini-QGP formation in  $pp$  collisions the experimental data prefer somewhat larger values:  $\alpha_s^{fr} \approx 0.6$  (0.5) for RHIC (LHC). For these values of  $\alpha_s^{fr}$  at  $p_T \gtrsim 10$  GeV the decrease of  $R_{AA}^{st}$  in the numerator of (6) reasonably compensates the presence of  $R_{pp} < 1$  in the denominator of (6). This allows one to have approximately the same  $R_{AA}$  in both scenarios of  $pp$  collisions. However, this procedure acts in a different way for heavy quarks. It results in some differences in the heavy-to-light ratios of the nuclear modification factors  $R_{AA}$  for the scenarios with and without mini-QGP production in  $pp$  collisions.

In Fig. 2 we show the ratios  $R_{AA}^D/R_{AA}^\pi$  and  $R_{AA}^B/R_{AA}^\pi$  for Au+Au collisions at  $\sqrt{s} = 0.2$  TeV and Pb+Pb collisions at  $\sqrt{s} = 2.76$  TeV (for 0 – 5% centrality class) obtained for  $R_{AA}$  without (solid curves) and with (dashed curves) inclusion of the  $R_{pp}$  factors for 0 – 5% central  $AA$  collisions at RHIC and LHC. We have used the above values of  $\alpha_s^{fr}$ : 0.5 (0.4) for RHIC (LHC) in the standard scenario, and 0.6 (0.5) for RHIC (LHC) in the scenario with the mini-QGP formation in  $pp$  collisions. From Fig. 2 one sees that the mini-QGP formation can sizeably reduce the heavy-to-light ratios at  $p_T \lesssim 20$  GeV for RHIC and at  $p_T \lesssim 50$  GeV for LHC. At  $p_T \sim 10$  GeV (interseting in the context of the present situation with the “heavy quark puzzle”) in the mini-QGP scenario the ratio  $R_{AA}^D/R_{AA}^\pi$  becomes smaller by  $\sim 20 - 30\%$ , and

$R_{AA}^B/R_{AA}^\pi$  by  $\sim 15 - 25\%$ . To illustrate better the role of the increase of  $\alpha_s^{fr}$  in the mini-QGP scenario, we show in Fig. 2 the ratios for  $R_{AA}$  obtained with inclusion of  $R_{pp}$  in (6), but for  $R_{AA}^{st}$  evaluated without renormalization of  $\alpha_s^{fr}$  (dotted curves). By comparing the results for two choices of  $\alpha_s^{fr}$  one can see that the renormalization of  $\alpha_s^{fr}$  gives a sizeable reduction of  $R_{AA}^D/R_{AA}^\pi$ , but practically does not change  $R_{AA}^B/R_{AA}^\pi$ . Thus, from Fig. 2 we see that the mini-QGP formation in  $pp$  collisions weakens the flavor dependence of the nuclear modification factors  $R_{AA}$  at RHIC and LHC energies. However, the effect is not very strong, and due to rather large experimental error bars for the available heavy flavor  $R_{AA}$  data [18–21] the situation with their description in the scenario with the mini-QGP production in  $pp$  collisions does not differ significantly from our previous analysis [14, 15] within the standard scenario without the QGP formation in  $pp$  collisions. For this reason we do not present a comparison with experiment in the present letter. Anyway, for a conclusive comparison between theory and experiment we need more accurate data on the  $R_{AA}$  for heavy flavors at higher  $p_T$ .

#### IV. SUMMARY

The medium FSI effects should modify high- $p_T$  jets in  $pp$  collisions if the mini-QGP production occurs. We

have studied the flavor dependence of the medium modification factor  $R_{pp}$  in this scenario. We evaluated  $R_{pp}$  for pions,  $D$  and  $B$  mesons for RHIC ( $\sqrt{s} = 0.2$  TeV) and LHC ( $\sqrt{s} = 2.76$  TeV) energies. We have observed that at  $p_T \sim 10$  GeV the pion spectrum is suppressed by  $\sim 20 - 30$  ( $25 - 35$ )% for RHIC (LHC), for  $D$  ( $B$ ) mesons the effect is smaller by a factor of  $\sim 0.7 - 0.8$  ( $0.5$ ) than for pions. The flavor hierarchy  $R_{pp}^\pi < R_{pp}^D < R_{pp}^B$  is held at  $p_T \lesssim 20$  GeV for RHIC and at  $p_T \lesssim 70$  GeV for LHC. We demonstrated that this gives a sizeable reduction of the heavy-to-light ratios of the nuclear modification factors  $R_{AA}$ . At  $p_T \sim 10$  GeV the ratio  $R_{AA}^D/R_{AA}^\pi$  is suppressed by  $\sim 20 - 30\%$  and  $R_{AA}^B/R_{AA}^\pi$  by  $\sim 15 - 25\%$  as compared to that in the standard scenario without the QGP production in  $pp$  collisions.

#### Acknowledgments

This work is supported in part by the grant RFBR 15-02-00668-a and the program SS-3139.2014.2.

#### References

- 
- [1] B.G. Zakharov, Phys. Rev. Lett. **112**, 032301 (2014) [arXiv:1307.3674].
  - [2] P. Bozek, Acta Phys. Polon. B**41**, 837 (2010) [arXiv:0911.2392].
  - [3] J. Casalderrey-Solana and U.A. Wiedemann, Phys. Rev. Lett. **104**, 102301 (2010) [arXiv:0911.4400].
  - [4] R. Campanini, G. Ferri, and G. Ferri, Phys. Lett. B**703**, 237 (2011) [arXiv:1106.2008].
  - [5] V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, and A. Warburton, Phys. Rev. C**86**, 044902 (2012) [arXiv:1203.6679].
  - [6] A. Bzdak, B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. C**87**, 064906 (2013) [arXiv:1304.3403].
  - [7] E. Shuryak and I. Zahed, Phys. Rev. C**88**, 044915 (2013) [arXiv:1301.4470].
  - [8] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1009**, 091 (2010).
  - [9] R. Field, Acta Phys. Polon. B**42**, 2631 (2011) [arXiv:1110.5530].
  - [10] H.L. Vargas, for the ALICE Collaboration, J. Phys. Conf. Ser. **389**, 012004 (2012) [arXiv:1208.0940].
  - [11] B.G. Zakharov, J. Phys. G**41**, 075008 (2014) [arXiv:1311.1159].
  - [12] B.G. Zakharov, JETP Lett. **88**, 781 (2008).
  - [13] B.G. Zakharov, JETP Lett. **93**, 683 (2011) [arXiv:1105.2028].
  - [14] B.G. Zakharov, JETP Lett. **96**, 616 (2013) [arXiv:1210.4148].
  - [15] B.G. Zakharov, J. Phys. G**40**, 085003 (2013) [arXiv:1304.5742].
  - [16] B.G. Zakharov, JETP Lett. **63**, 952 (1996); *ibid* **65**, 615 (1997); **70**, 176 (1999); Phys. Atom. Nucl. **61**, 838 (1998).
  - [17] T. Renk, J. Phys. Conf. Ser. **509**, 012022 (2014) [arXiv:1309.3059].
  - [18] S.S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **96**, 032301 (2006).
  - [19] B.I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **98**, 192301 (2007) [arXiv:nucl-ex/0607012], Erratum-*ibid.* 106 (2011) 159902.
  - [20] S. Sakai, for the ALICE Collaboration, contribution to the Quark Matter 2012 Conf., <http://qm2012.bnl.gov/default.asp>.
  - [21] B. Abelev *et al.* [ALICE Collaboration], JHEP **1209**, 112 (2012) [arXiv:1203.2160].
  - [22] Y.L. Dokshitzer and D.E. Kharzeev, Phys. Lett B**519**, 199 (2001).
  - [23] P. Aurenche and B.G. Zakharov, JETP Lett. **90**, 237 (2009) [arXiv:0907.1918].
  - [24] B.A. Kniehl, G. Kramer, and B. Potter, Nucl. Phys. B**582**, 514 (2000).
  - [25] T. Sjostrand, L. Lonnblad, S. Mrenna, and P. Skands, arXiv:hep-ph/0308153.
  - [26] B.G. Zakharov, JETP Lett. **80**, 617 (2004) [hep-ph/0410321].
  - [27] B.G. Zakharov, JETP Lett. **86**, 444 (2007) [arXiv:0708.0816].
  - [28] P. Lévai and U. Heinz, Phys. Rev. C**57**, 1879 (1998).
  - [29] O. Kaczmarek and F. Zantow, Phys. Rev. D**71**, 114510

- (2005).
- [30] N.N. Nikolaev and B.G. Zakharov, Phys. Lett. B**327**, 149 (1994).
  - [31] Yu.L. Dokshitzer, V.A. Khoze, and S.I. Troyan, Phys. Rev. D**53**, 89 (1996).
  - [32] B. Müller and K. Rajagopal, Eur. Phys. J. C**43**, 15 (2005) [arXiv:hep-ph/0502174].
  - [33] L. McLerran, M. Praszalowicz, and B. Schenke, arXiv:1306.2350.
  - [34] S. Borsanyi, Nucl. Phys.A**904-905**, 270c (2013) [arXiv:1210.6901].
  - [35] B.I. Abelev *et al.* [STAR Collaboration ], Phys. Rev. C**79**, 034909 (2009).
  - [36] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1108**, 141 (2011).
  - [37] P. Aurenche, M. Fontannaz, J.P. Guillet, B.A. Kniehl, and M. Werlen, Eur. Phys. J. C**13**, 347 (2000) [hep-ph/9910252].
  - [38] M. Cacciari, P. Nason, and R. Vogt, Phys. Rev. Lett. **95**, 122001 (2005) [hep-ph/0502203].
  - [39] M. Cacciari *et al.*, JHEP **1210**, 137 (2012) [arXiv:1205.6344].